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13. ABSTRACT (*Maximum 200 words*)

This research is directed toward basic studies on millimeter, microwave, and optical wave propagation and scattering in geophysical media, such as, hydrometeors, smog, dust, snow, fog, atmospheric turbulence, terrain, and vegetation. These studies are aimed at understanding the physical mechanisms of the interactions between waves and geophysical media and developing new techniques in communications in adverse weather, detection and identification of objects and remote sensing in the geophysical environment. Our findings include a polarimetric scattering model for high slope rough surfaces which are often encountered in practice and a study on low grazing angle scattering which is directly applicable to the Army mission when both the transmitter and receiver are close to the surface. We also devised a new interferometric technique to detect a target in the presence of clutter (30728.14-GS) and a disclosure was made to the Office of Technology Transfer, University of Washington, on "detection of a buried object using correlation technique." We also devised a technique to determine the average height profile of rough surfaces and a general formulation for pulse scattering. Our emphasis is on the development of angular, frequency and polarization correlation techniques applicable to remote sensing, target detection and communications in the geophysical environment.

14. SUBJECT TERMS
Wave propagation, scattering, polarimetric scattering, interferometry, clutter reduction, target detection, geophysical media

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WAVE PROPAGATION AND SCATTERING IN GEOPHYSICAL MEDIA

FINAL REPORT

Akira Ishimaru

November 25, 1996

U.S. Army Research Office

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University of Washington

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TABLE OF CONTENTS

I. STATEMENT OF THE PROBLEM STUDIED

Our goal is to conduct research on millimeter and optical wave propagation and scattering as applied to geophysical media, such as, hydrometeors, fog, smoke, ice, snow, dust, vegetation, terrain, and atmospheric turbulence. These studies are aimed at understanding the physical mechanisms of the interactions between waves and geophysical media and at developing new techniques in communications in adverse weather, detection and identification of objects in geophysical media, and remote sensing of the characteristics of geophysical media.

Our emphasis is on combined use of three approaches: theoretical, experimental, and numerical. We have constructed a carefully controlled microwave and millimeter wave scattering measurement system capable of measuring all the polarization characteristics and amplitude and phase correlations for X and Ku bands and 75-100 Ghz. We also constructed an optical scattering system capable of measuring the complete polarization characteristics and the Stokes vector and Mueller matrix. We have conducted extensive Monte-Carlo numerical simulations of wave scattering by random media. These experimental and numerical studies are essential to guide the development of the theoretical models of wave scattering by geophysical media.

II. SUMMARY OF THE MOST IMPORTANT RESULTS

2-1 Tasks Completed:

2-1-1 *Theoretical model for polarimetric scattering by high slope rough surfaces*

Rough surface scattering is an important factor in understanding clutter due to terrain. Conventional rough surface scattering theories are applicable to surfaces with small height variations or with large radii of curvature. Many practical geophysical terrain surfaces, such as, snow and soil have high slopes and are outside the range of validity of the conventional theoretical models. We have completed a general polarimetric scattering theory applicable to rough surfaces with high slopes which may be applicable to various geophysical surfaces.

2-1-2 *Propagation and scattering near the terrain surfaces*

Many practical problems in the Army mission require understanding of the wave propagation when both the transmitter and receiver are close to the terrain, and thus the surface clutter effects become significant. This problem is called the "low grazing angle scattering" and is one of the outstanding theoretical problems today. We have initiated experimental and theoretical studies on this problem and verified experimentally that the ratio of vertical to horizontal backscattering is close to unity. This has also been shown by others, but it has been a difficult theoretical challenge. With the well controlled experimental results, we intend to construct a theoretical model for this problem which will have important applications in the Army mission.

2-2-3 *Target detection in a clutter environment*

We have made extensive studies on the new angular correlation effects of the scattered wave called the "memory effect." This shows strong correlations between the scattered waves under certain conditions. This memory effect is drastically different depending on whether the medium is deterministic or random. Based on this study, we recently developed a technique on "detection of a buried object using a correlation method"

(30728.14-GS). This was disclosed to the Office of Technology Transfer at the University of Washington as a possible invention. Further studies are continuing to refine the technique to include volume and surface clutter effects and the use of polarization and frequency correlations.

2-1-4 *Interferometric technique for determining the average surface profiles of rough surfaces*

In recent years, there has been increasing interest in using the interferometric technique to measure the surface profile. For example, InSAR (SAR interferometry) is used for topographic mapping of the terrain. We have initiated a theoretical study of this problem and obtained a theoretical model based on Kirchhoff approximations. This has been confirmed by millimeter wave experiments.

2-1-5 *Pulse scattering*

We have completed a theoretical study of pulse scattering by rough surfaces making use of the two-frequency coherence function formulations. The analytical results have been compared with numerical Monte-Carlo simulations and millimeter wave experiments.

2-2 Most Important Results:

2-2-1 High slope rough surface scattering theory predicts the enhanced backscattering effect which is not present for conventional low slope scattering. Our theoretical models should be useful in many geophysical media and terrain where high slopes are often present.

2-2-2 In the Army mission, both the transmitter and receiver can be near the surface and the effects of clutter due to terrain can be significant. Our results on low grazing angle scattering are promising, but preliminary, and further studies are being made.

2-2-3 We have obtained good results showing the existence of an object in the presence of surface clutter. Figure 1 shows that the conventional intensity measurement cannot discriminate between the target and the clutter, but our new technique clearly detects the object (30728.14-GS).

2-2-4 We have a theoretical model for determining the average surface height profile of rough surfaces, and the results are compared with millimeter wave experiments showing good agreement. This is now being extended to include complete polarimetric characteristics.

2-2-5 Our pulse scattering model clearly shows the effects of beam size, average height profile, and correlation distance of the rough surface. These should lead to the determination of useful information on coherence bandwidth, coherence time, and time-frequency relationships.

2-3 Impact for Science and Engineering:

First, we obtained a new theoretical model for polarimetric scattering for high slope rough surfaces. This has not been reported before and may lead to more practical models which are applicable to actual terrain. Secondly, the low grazing problem is one of the outstanding theoretical problems, and we have made initial studies on this problem which has not been well understood. Thirdly, our correlation technique for discriminating an object against clutter is successful and further work will give a useful technique for target

detection. Forth, our new formulation for height profile of rough surfaces will be a first step in extending and improving existing topographic mapping techniques. Fifth, our theoretical pulse scattering models should yield more general formulations for coherence bandwidth and coherence time in a clutter environment.

2-4 Relationships to Other Programs or Projects:

We have collaborative relationships with NCAR (National Center for Atmospheric Research) and Charlie Le, a graduate student, has spent several months with them working on atmospheric remote sensing problems. Our study on determination of the average height profile is closely related to the InSAR project at JPL.

III. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD

1. K. Yoshitomi, A. Ishimaru, J.-N. Hwang, and J. S. Chen, "Surface roughness determination using spectral correlations of scattered intensities and an artificial neural network technique," *IEEE Transactions on Antennas and Propagation,* 41:4, pp. 498-502, April 1993.

2. C. M. Lam and A. Ishimaru, "Mueller matrix representation for a slab of random medium with discrete particles and random rough surfaces with moderate surface roughness," *Waves in Random Media,* 3:2, pp. 111-125, April 1993.

3. C. M. Lam and A. Ishimaru, "Calculation of Mueller matrices and polarization signatures for a slab of random medium using vector radiative transfer," *IEEE Transactions on Antennas and Propagation,* 41:7, pp. 851-862, July 1993.

4. P. Phu, A. Ishimaru, and Y. Kuga, "Controlled millimeter-wave experiments and numerical simulations on the enhanced backscattering from one-dimensional very rough surfaces," *Radio Science,* 28:4, pp. 533-548, July-August 1993.

5. V. I. Tatarskii, A. Ishimaru, and V. U. Zavorotny, editors, *Wave Propagation in Random Media (Scintillation),* 487 pages, SPIE Press, Bellingham, Washington and Institute of Physics Publishing, Bristol, England, 1993.

6. Y. Kuga, A. Ishimaru, and D. Rice, "Velocity of coherent and incoherent electromagnetic waves in a dense strongly scattering medium," *Physical Review B,* 48:17, pp. 155-158, November 1993.

7. L. Tsang, C. H. Chan, H. Sangani, A. Ishimaru, and P. Phu, "A banded matrix iterative approach to Monte Carlo simulations of large-scale random rough surface scattering: TE case," *Journal of Electromagnetic Waves and Applications,* 7:9, pp. 1185-1200, 1993.

8. L. Tsang, C. H. Chan, K. Pak, H. Sangani, A. Ishimaru, and P. Phu, "Monte Carlo simulations of large-scale composite random rough-surface scattering based on the banded-matrix iterative approach," *Journal of the Optical Society of America A,* 11:2, pp. 691-696, February 1994.

9. C. M. Lam and A. Ishimaru, "Mueller matrix calculation for a slab of random medium with both random rough surfaces and discrete particles," *IEEE Transactions on Antennas and Propagation,* 42:2, pp. 145-156, February 1994.

10. A. Ishimaru, L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse broadening and two-frequency mutual coherence function of the scattered wave from rough surfaces," *Waves in Random Media,* 4:2, pp. 139-148, April 1994.

11. A. Ishimaru, "Optical multiple scattering by particles," *Particle and Particle Systems Characterization,* II, pp. 183-188, VCH Publications, Weinheim, Germany, 1994.

12. P. Phu, A. Ishimaru, and Y. Kuga, "Copolarized and cross-polarized enhanced backscattering from two-dimensional very rough surfaces at millimeter wave frequencies," *Radio Science,* 29:5, pp. 1275-1291, September-October 1994.

13. A. Ishimaru, L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse broadening of enhanced backscattering from rough surfaces," *Waves in Random Media,* 4:4, pp. 453-465, October 1994.

14. A. Ishimaru, L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse Scattering by Rough Surfaces," *Ultra-Wideband, Short-Pulse Electromagnetics 2,* L. Carin and L. B. Felsen, editors, pp. 431-438, Plenum Press, New York, 1995.

15. T.-K. Chan, Y. Kuga, A. Ishimaru, and C. T. C. Le, "Experimental studies of bistatic scattering from two-dimensional conducting random rough surfaces," *IEEE Transactions on Geoscience and Remote Sensing*, 34:3, pp. 674-680, May 1996.

16. C. T. C. Le, Y. Kuga and A. Ishimaru, "Angular correlation function based on the second-order Kirchhoff approximation and comparison with experiments," *Journal of the Optical Society of America A,* 13:5, pp. 1057-1067, May 1996.

17. J. T. Johnson, L. Tsang, R. T. Shin, K. Pak, C. H. Chan, A. Ishimaru, and Y. Kuga, "Backscattering enhancement of electromagnetic waves from two-dimensional perfectly conducting random rough surfaces: A Comparison of Monte Carlo simulations with experimental data," *IEEE Transactions on Antennas and Propagation*, 44:5, pp. 748-756, May 1996.

18. M. A. Moehring, J. A. Ritcey, and A. Ishimaru, "Sizing emboli in blood using pulse Doppler ultrasound–II: Effects of beam refraction," *IEEE Transactions on Biomedical Engineering*, 43:6, pp. 581-588, June 1996.

19. A. Ishimaru, C. T. C. Le, Y. Kuga, L. Ailes-Sengers, and T.-K. Chan, "Polarimetric scattering theory for high slope rough surfaces," (Summary) *Journal of Electromagnetic Waves and Applications,* 10:4, pp. 489-491, 1996.

20. T.-K. Chan, Y, Kuga, and A. Ishimaru, "Angular memory effect of millimeter-wave scattering from two-dimensional conducting random rough surfaces," *Radio Science,* 31:5, pp. 1067-1076, September-October 1996.

21. A. Ishimaru and Y. Kuga, "Recent advances in multiple scattering theories and applications," Special issue on Electromagnetic Theory – Foundations and Applications, *IEICE Transactions on Electronics*, E79-C:10. pp. 1295-1299, October 1996 (Invited paper).

22. Y. Kuga, C. T. C. Le, A. Ishimaru, and L. Ailes-Sengers, "Analytical, experimental, and numerical studies of angular memory signatures of waves scattered from one-dimensional rough surfaces," accepted, *IEEE Transactions on Geoscience and Remote Sensing*, 1996.

23. Y. Kuga, T.-K. Chan, and A. Ishimaru, "Detection of a target embedded in clutter using the angular memory effect," submitted to the *IEEE Transactions on Antennas and Propagation*, 1995.

24. A. Ishimaru, C. T. C. Le, Y. Kuga, J.-H. Yea, and K. Pak, "Angular Memory Interferometric Technique for Retrieving the Mean Height Profile of Rough Surfaces," submitted to the *IEEE Transactions on Geoscience and Remote Sensing*, 1996.

IV. PAPER PRESENTATIONS AT MEETINGS DURING THIS PERIOD

1. A. Ishimaru, "A Smoothing Method for Rough Surface Scattering," URSI Radio Science Meeting, The University of Michigan, Ann Arbor, Michigan, June 1993.

2. D. J. Rice, Y. Kuga, and A. Ishimaru, "Propagation Constant of Coherent Microwaves in a Dense Distribution of Nontenuous Spheres," URSI Radio Science Meeting, The University of Michigan, Ann Arbor, Michigan, June 1993.

3. A. Ishimaru, P. Phu, and J. S. Chen, "High Slope Second-Order Theory of Scattering from Very Rough Surfaces," Progress in Electromagnetics Research Symposium (PIERS), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 1993.

4. C. M. Lam and A. Ishimaru, "Recent Advances in Vector Radiative Transfer Theory for Random Media with Random Rough Surfaces and Discrete Particles," Progress in Electromagnetics Research Symposium (PIERS), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 1993.

5. P. Phu, A. Ishimaru, Y. Kuga, and B. Kitichotpanit, "Copolarized and Cross Polarized Enhanced Backscattering from Two-Dimensional Very Rough Surfaces at Millimeter-Wave Frequencies," Progress in Electromagnetics Research Symposium (PIERS), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 1993.

6. Y. Kuga, D. J. Rice, and A. Ishimaru, "The Velocity of Electromagnetic Waves in a Dense Strongly Scattering Medium," Progress in Electromagnetics Research Symposium (PIERS), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 1993.

7. Y. Kuga, B. Kitichotpanit, A. Ishimaru, and C. Clayton, "Coherent Reflectivity and Bistatic Cross Section of a Dense Strongly Scattering Medium," Progress in Electromagnetics Research Symposium (PIERS), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 1993.

8. A. Ishimaru, P. Phu, and Y. Kuga, "Pulse Beam Wave Scattering from One-Dimensional Rough Surfaces: Experimental and Numerical Studies," International Geoscience and Remote Sensing Symposium (IGARSS'93), Tokyo, Japan, August 1993.

9. A. Ishimaru, "Optical Multiple Scattering by Particles," Third International Conference on Optical Particle Sizing, Yokohama, Japan, August 1993 (Plenary Speaker).

10. A. Ishimaru, "Theories of Enhanced Backscattering by Rough Surfaces," XXIV General Assembly of the International Union of Radio Science (URSI), Kyoto, Japan, August 1993.

11. Y. Kuga, A. Ishimaru, and D. Rice, "The Velocity of Electromagnetic Waves in a Dense Scattering Medium," XXIV General Assembly of the International Union of Radio Science (URSI), Kyoto, Japan, August 1993.

12. A. Ishimaru, L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse Broadening and Two-Frequency Mutual Coherence Function of the Scattered Wave from Rough Surfaces," National Radio Science Meeting, Boulder, Colorado, January 1994.

13. A. Ishimaru, "Spectral Broadening and Remote Sensing for Random Media," NASA-UCLA Workshop on Laser Propagation in Atmospheric Turbulence, University of California, Los Angeles, February 1994 (Invited Speaker).

14. A. Ishimaru, "Pulse Scattering by Rough Surfaces," Second International Conference on Ultra-Wideband, Short-Pulse Electromagnetics, Polytechnic University, Brooklyn, New York, April 1994 (Invited Speaker).

15. J. C. Machado, A. Ishimaru, and R. A. Sigelmann, "Mode Conversion Effect on the Scattering of Elastic Spheres Near Resonance," 1994 IEEE International Ultrasonics Symposium, Cannes, France, 1994.

16. S. Yano, A. Ishimaru, and T. Ogawa, "Quadruple Refraction of HF-Waves in the Ionosphere," URSI Radio Science Meeting, Seattle, Washington, June 1994.

17. C. Le, A. Ishimaru, Y. Kuga, and P. Phu, "Theoretical and Experimental Studies of Millimeter-Wave Scattering from Well Characterized Two-Dimensional Rough Surfaces," URSI Radio Science Meeting, Seattle, Washington, June 1994.

18. L. Ailes-Sengers, A. Ishimaru, and D. P. Winebrenner, "Broadening of Gaussian Pulses Scattered by Rough Surfaces," URSI Radio Science Meeting, Seattle, Washington, June 1994.

19. G. Kim and A. Ishimaru, "Hyperthermia Modeling for an Infinite Two-Layer Concentric Cylinder Using Matrix Optimization," URSI Radio Science Meeting, Seattle, Washington, June 1994.

20. A. Ishimaru, L. Ailes-Sengers, P. Phu, D. P. Winebrenner, and Y. Kuga, "Frequency and Angular Correlations of Waves Scattered by Rough Surfaces," Progress in Electromagnetics Symposium (PIERS), Noordwijk, The Netherlands, July 1994.

21. A. Ishimaru, L. Ailes-Sengers, P. Phu, and D. P. Winebrenner, "Pulse Broadening of the Enhanced Backscattering from Rough Surfaces," International Geoscience and Remote Sensing Symposium (IGARSS'94), California Institute of Technology, Pasadena, California, August 1994.

22. L. Ailes-Sengers, A. Ishimaru, and Y. Kuga, "Frequency and Angular Correlations of Electromagnetic Waves Scattered by Rough Surfaces," National Radio Science Meeting, Boulder, Colorado, January 1995.

23. A. Ishimaru, "Imaging Through Random Media," Kyushu University, Fukuoka, Japan, April 1995.

24. A. Ishimaru, Y. Kuga, L. Ailes-Sengers, C. Le, and T.-K. Chan, "Polarimetric Scattering Theory for High-Slope Rough Surfaces," CEA/CESTA Workshop on Light Scattering and Related Phenomena, Arcachon, France, May 1995.

25. A. Ishimaru, L. Ailes-Sengers, and Y. Kuga, "Electromagnetic Scattering by High-Slope Rough Random Surfaces, Pulse Scattering, Angular Memory Effects and Enhanced Backscattering," International Symposium on Electromagnetic Theory, St. Petersburg, Russian, May 1995.

26. L. Ailes-Sengers, A. Ishimaru, and Y. Kuga, "Analytical and Experimental Studies of Backscattering of Electromagnetic Waves from High-Slope Rough Surfaces," USNC/URSI Radio Science Meeting, Newport Beach, California, June 1995.

27. H. Zhao, Y. Kuga, and A. Ishimaru, "Bistatic Scattering Characteristics of Surface Waves on Dielectric Rough Surfaces," USNC/URSI Radio Science Meeting, Newport Beach, California, June 1995.

28. L. Ailes-Sengers, A. Ishimaru, and Y. Kuga, "Analytical and Experimental Studies of Electromagnetic Waves Scattered by Two-Dimensional, Dielectric Very Rough Surfaces," International Geoscience and Remote Sensing Symposium (IGARSS'95), Firenze, Italy, July 1995.

29. C. Le, J. Vivekanandan, and A. Ishimaru, "Spatial Resolution Enhancement Technique for Weather Radar Images," Progress in Electromagnetics Research Symposium (PIERS), Seattle, Washington, July 1995.

30. L. Ailes-Sengers, A. Ishimaru, and Y. Kuga, "Pulse Broadening Due to Scattering by Two-Dimensional Very Rough Surfaces," Progress in Electromagnetics Research Symposium (PIERS), Seattle, Washington, July 1995.

31. B. Koala, A. Ishimaru, and Y. Kuga, "Experiment on Grazing Angle Pulse Scattering from Rough Surfaces," Progress in Electromagnetics Research Symposium (PIERS), Seattle, Washington, July 1995.

32. H. Zhao, Y. Kuga, and A. Ishimaru, "Observations of Backscattering Enhancement from Surface Waves on Dielectric Rough Surfaces," Progress in Electromagnetics Research Symposium (PIERS), Seattle, Washington, July 1995.

33. T.-K. Chan, Y. Kuga, and A. Ishimaru, "Detailed Experimental Studies on Scattering from Two-Dimensional Conducting Rough Surfaces," Progress in Electromagnetics Research Symposium (PIERS), Seattle, Washington, July 1995.

34. Y. Kuga, C. T. C. Le, and A. Ishimaru, "Analytical, Experimental, and Numerical Studies of Angular Memory Signatures of Waves Scattered from One-dimensional Rough Surfaces," International Geoscience and Remote Sensing Symposium (IGARSS'96), Lincoln, Nebraska, May 1996.

35. A. Ishimaru, C. T. C. Le, Y. Kuga, J.-H. Yea, K. Pak, and T.-K. Chan, "Interferometric Technique for Determining the Average Height Profile of Rough Surfaces," International Geoscience and Remote Sensing Symposium (IGARSS'96), Lincoln, Nebraska, May 1996.

36. T.-K. Chan, Y. Kuga, and A. Ishimaru, "Detection of a Target in a Homogeneous Medium using Angular Correlation Function," International Geoscience and Remote Sensing Symposium (IGARSS'96), Lincoln, Nebraska, May 1996.

37. A. Ishimaru, Y. Kuga, C. T. C. Le, and T.-K. Chan, "Angular, Frequency, Time and Polarization Correlations of Waves Scattered by Rough Surfaces and Applications to Surface Profile Determination and Object Detection," Workshop on Rough Surface Scattering, Sponsored by the University of California, Yountville, California, June 1996.

38. A. Ishimaru, Y. Kuga, and C. T. C. Le, "Interferometry and Memory Effect for Rough Surface Scattering," URSI Radio Science Meeting, Baltimore, Maryland, July 1996.

39. A. Ishimaru, "Recent Advances in Radiative Transfer and Multiple Scattering," International Radiation Symposium (IRS'96), Geophysical Institute, University of Alaska Fairbanks, Alaska, August 1996.

40. A. Ishimaru, Y. Kuga, C. T. C. Le, and T.-K. Chan, "Interferometric Technique to Determine Surface Profiles and to Detect an Object in Random Media," XXV General Assembly of the International Union of Radio Science (URSI), Lille, France, August 1996.

41. A. Ishimaru, "Imaging in Biological and Environmental Random Media," International Symposium on Antennas and Propagation (ISAP), Chiba, Japan, September 1996.

42. A. Ishimaru, Y. Kuga, C. T. C. Le, and T.-K. Chan, "Angular, Frequency, Time and Polarization Correlations of Scattered Waves," Progress in Electromagnetics Research Symposium (PIERS), City University of Hong Kong, Kowloon, Hong Kong, January 1997.

V. PARTICIPATING SCIENTIFIC PERSONNEL

Akira Ishimaru, Principal Investigator
Yasuo Kuga, Co-Investigator
Phillip Phu, Awarded Ph.D. October 1993
Craig Clayton, Awarded M.S. March 1994
Lynn Ailes-Sengers, Awarded Ph.D. May 1996
Charlie Le, Awarded Ph.D. August 1996
T. K. Chan, Awarded M.S. June 1995, Passed Ph.D. General Exam October 1996

Akira Ishimaru, Elected to the National Academy of Engineering, October 1996.

V1. TECHNOLOGY TRANSFER

Our study on correlation techniques applicable to geophysical media resulted in a disclosure of "Detection of a buried object using a correlation method" by Y. Kuga, T. K. Chan, and A. Ishimaru to the Office of Technology Transfer, University of Washington, December 27, 1995. This is based on the idea that the correlations of the scattered wave are drastically different depending on whether the object or medium is deterministic and random (30728.14-GS).

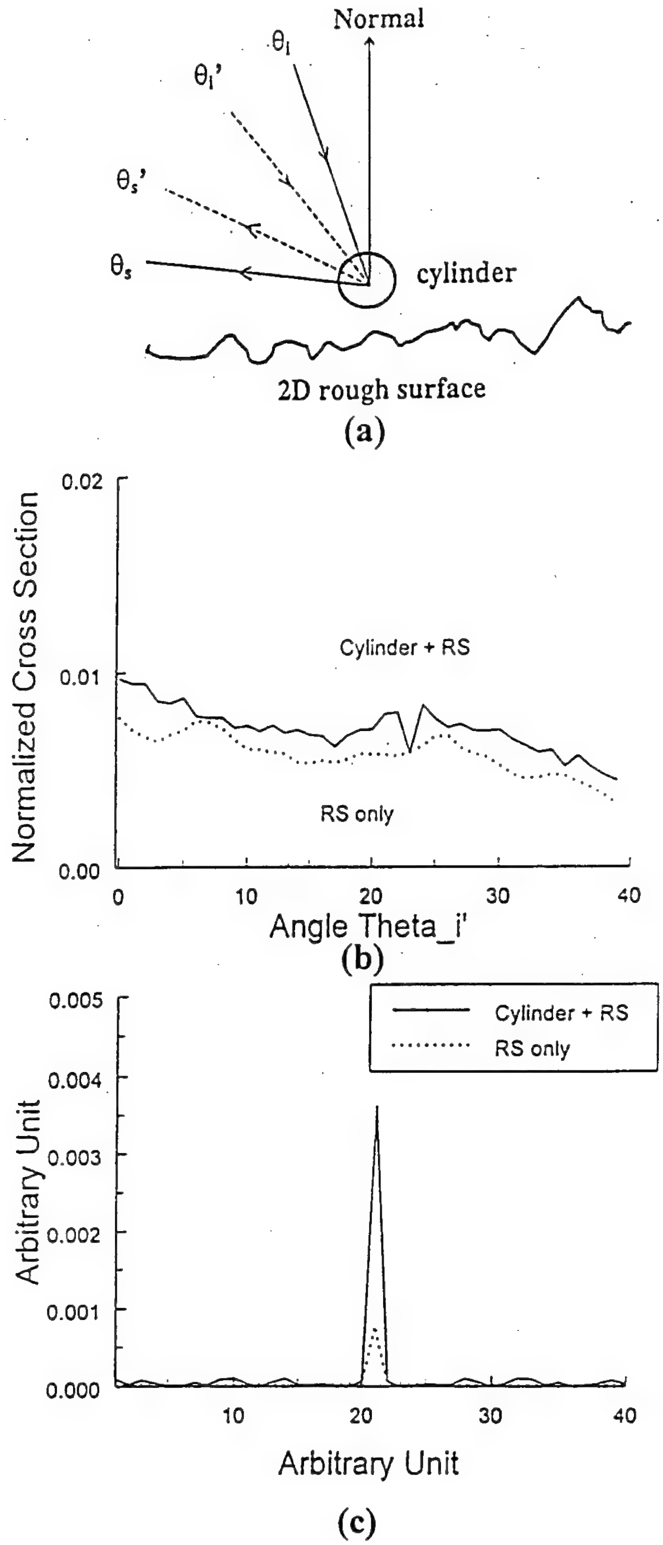

Fig. 1. Detection of a target embedded in clutter.

(a) experimental setup. A 3-mm cylinder located at a distance of 5λ above a two-dimensional random rough surface (rms height = 1λ, correlation length = 2λ), where λ = 3mm.

(b) conventional measured cross-section.

(c) measured angular correlation clearly shows the target.

From Kuga, Chan, and Ishimaru, (30728.14-GS)

VII. ABSTRACTS OF PUBLISHED PAPERS

[27] A. Ishimaru, R. Woo, J. W. Armstrong, and D. C. Blackman, "Multiple scattering calculations of rain effects," *Radio Sci.*, vol. 17, no. 6, pp. 1425–1433, Nov.–Dec. 1982.
[28] A. Ishimaru and R. L. T. Cheung, "Multiple scattering effects on wave propagation due to rain," *Ann. des. Telecom.*, vol. 35, nos. 11–12, pp. 373–379, Nov.–Dec. 1980.
[29] D. C. Hogg and T. S. Chu, "The role of rain in satellite communications," *Proc. IEEE*, vol. 63, pp. 1308–1331, Sept. 1975.
[30] D. Cox, H. Arnold, and H. Hoffman, "Measured bounds on rain scatter coupling between space-earth radio paths," *IEEE Trans. Antennas Propagat.*, vol. 30, no. 3, pp. 493–497, May, 1992.

Surface Roughness Determination Using Spectral Correlations of Scattered Intensities and an Artificial Neural Network Technique

Kuniaki Yoshitomi, Akira Ishimaru, Jeng-Neng Hwang, and Jei Shuan Chen

Abstract—**An artificial neural network (ANN) technique is applied to the determination of the rms height and the correlation distance of one-dimensional rough surfaces. The surface is illuminated by a beam wave, and the intensity correlations of the scattered wave at two wavelengths in the specular and backward directions are used to determine the roughness parameters. Scattered intensity correlations calculated by Monte Carlo simulations are used to train the ANN, and two methods, the explicit inversion method and the iterative constrained inversion method, are used to perform the inversion. The inversion values are compared with the target values, and the iterative constrained method is shown to give smaller errors, but requires longer computer CPU time.**

I. Introduction

Noncontacting measurements of surface roughness parameters have attracted considerable attention in recent years [1]–[7]. When a wave is scattered from a rough surface, the characteristics of the scattered wave depend on the rms surface height, σ, the correlation distance, l, of the surface roughness, and the refractive indices of the medium. It should, therefore, be possible to determine the roughness parameters, σ and l, by appropriate measurements of the scattered field.

This paper first examines the forward problem of calculating the spectral correlations of speckle patterns of two different wavelengths in the backward and specular directions [3]. A beam wave is incident on the surface and the scattered fields are calculated using the surface integral equation and the Monte Carlo simulation. The surface is one-dimensional, the Dirichlet condition is satisfied on the surface, and the surface spectrum is Gaussian. This forward problem is used to determine the range of parameters which are effective for inversion.

Next, the inverse problem of finding the surface parameters, σ and l, from the measurement is considered. Here we use an artificial neural network (ANN) technique [8]–[10]. The calculated spectral correlations for given surface parameters are used to train the ANN. An advantage of the ANN technique is that even though it may take a large amount of computer time to train the ANN, once the ANN is trained, the inverse problem of finding the surface parameters from the measured spectral correlations can be accomplished quickly. Numerical examples are given to show the effectiveness of the method.

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II. Forward Problem

Let us consider a beam wave incident on a one-dimensional Dirichlet rough surface (Fig. 1). The spectral correlations $r_{12}(\theta_0)$ in the specular direction and $r_{12}(-\theta_0)$ in the backward direction are defined by [3].

$$r_{12} = \frac{\langle i_1 i_2\rangle - \langle i_1\rangle\langle i_2\rangle}{[(\langle i_1^2\rangle - \langle i_1\rangle^2)(\langle i_2^2\rangle - \langle i_2\rangle^2)]^{1/2}}, \tag{1}$$

where $i_n (n = 1 \text{ or } 2)$ represents the speckle intensities of the two different wavelengths, λ_n, scattered from the same surface, and the scattered fields are obtained by the Monte Carlo simulation of the exact integral equation. The details of the simulation are given in [11] and [12]. The surface profile is generated by using a Gaussian spectral method. The incident wave is a tapered plane given by

$$\psi_{\text{in}}(\boldsymbol{r}) = e^{-i\boldsymbol{K}_{\text{in}}\cdot\boldsymbol{r}[1+W(\boldsymbol{r})]}e^{-(x-z\tan\theta_0)^2/g^2}, \tag{2}$$

where

$$W(\boldsymbol{r}) = [2(x + z\tan\theta_0)^2/g^2 - 1]/(kg\cos\theta_0)^2 \tag{3}$$

$$\boldsymbol{K}_{\text{in}} = k(\cos\theta_0\hat{x} - \sin\theta_0\hat{z}), \tag{4}$$

and g is the parameter that controls the tapering. The r_{12} depends on the number of independent scattering cells, $N = 2g/l$ (l is the correlation length of the surface) [3]. The optimum values of N are approximately 10 for effective inversion. The surface length, L, used is $L = 4g$.

Figs. 2 and 3 show the speckle correlation, r_{12}, versus the rms height, σ, for different correlation lengths, l, and the ratio of the wavelength. For each case, 1200 surface realizations are generated, and the speckle correlations are calculated using (1) and the ensemble average. Note that the curves for r_{12} are well separated in the range considered, showing that r_{12} is sensitive to the variations of σ and l. This feature is important and necessary for the following inversion process.

We used the parameter $g = 5\lambda$ in Figs. 2 and 3. Different values of g, $g = 2.5\lambda$ and 7.5λ, are used. For the smaller g, the curves of r_{12} shift upward and it becomes insensitive to correlation lengths. For the bigger g, the curves overlap and become ambiguous. Therefore, there should be an optimal value of g or an optimal beam spot size. $L = 4g = 20\lambda$ appears to be optimum.

III. Inverse Problem Using an ANN and Multilayered Perceptron

Determination of the surface parameters σ and l from the correlation, r_{12}, is the inverse mapping problem. We use the method based on an ANN [8]. By using ANN, once the training is done

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Mueller matrix representation for a slab of random medium with discrete particles and random rough surfaces with moderate surface roughness

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Abstract. Mueller matrices are calculated for a slab of random medium containing both Gaussian-statistical-type random rough surfaces and discrete spherical particles. The refractive indices of the surrounding media are different from the background refractive index of the random medium. Kirchhoff rough-surface scattering theory associated with the geometric-optics approach is used to calculate the waves scattered from the rough surfaces. The scattered waves contain both coherent and incoherent waves. This method applies to rough surfaces with moderate surface roughness. In addition, the scattered waves can be related to the incident waves by means of the transmittivity and reflectivity matrices. These matrices are used to determine a pair of boundary conditions for the vector radiative transfer equation. The multiple scattering due to the discrete particles is computed by solving the vector radiative transfer equation numerically. Numerical illustrations are given for the optical thickness of the slab from 0.4 to 5 and the mean size parameter of the particles with Gaussian distribution, $\langle ka \rangle$, from 0.3 to 1. The surface root-mean-square slope varies from 0.1 to 0.3. Mueller matrices which characterize the random medium are constructed from the scattered Stokes vectors due to four independent polarized incident waves. The Mueller matrices are found to have eight non-vanishing matrix elements and some symmetrical properties.

1. Introduction

Mueller matrices are important in radar polarimetry and remote sensing as they characterize a target or a random medium at the incident frequency. Once the Mueller matrices are known, the scattered waves at different angles can be determined for any polarized incident wave. The Mueller matrices contain both the intensities and the complete polarization states of the scattered waves. Therefore, the Mueller matrices provide more information about the scattered waves than the conventional intensity representation.

Calculations of Mueller matrices have been reported for several scatterers. Bickel *et al* calculated the Mueller matrices for a single sphere by the Rayleigh, Rayleigh–Gans approximations and the Mie solution [1]. Kattawar *et al* calculated the Mueller matrices for dielectric cubes by solving an integral equation [2]. Hofer *et al* employed the extended boundary condition method to compute the Mueller matrices for spheroids [3]. However, the multiple-scattering effect is not included in the above calculation. Lam and Ishimaru computed the Mueller matrices for a slab of random medium with planar boundary and discrete spherical particles with size distribution using the vector radiative transfer equation [4]. Mueller matrices for a slab of random medium with Gaussian-statistical-type random rough surfaces of small surface roughness and discrete spherical particles with size

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Calculation of Mueller Matrices and Polarization Signatures for a Slab of Random Medium Using Vector Radiative Transfer

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***Abstract*— The Mueller matrix which characterizes a slab of random medium containing spherical particles is calculated by using the vector radiative transfer theory. The vector radiative transfer equation is solved for arbitrarily polarized incident waves. The background refractive index of the slab is allowed to be different from the surrounding media. The scattering specific intensities for four independent polarized incident waves are calculated and used to construct the Mueller matrix. The Mueller matrix contains multiple scattering due to the randomly distributed particles governed by the vector radiative transfer theory. The calculated Mueller matrices are found to have symmetrical property and there are eight nonvanishing matrix elements. Polarization signatures are obtained at the backscattering direction from the Mueller matrix of the reflection side.**

I. Introduction

Multiple scattering occurs when an electromagnetic wave propagates through media such as rain, vegetation, ocean water, or biological particles. The information contained in the scattering wave may lead to methods of enhancing radar communications if the media are known and in determining the parameters of the unknown media for remote sensing problems. Such media are generally modeled by a homogeneous slab containing randomly distributed particles. Research in electromagnetic wave scattering from randomly distributed particles deals with the complete multiple scattering process in the context of Stokes vectors, Mueller matrices, particle sizes, reference angles, and polarization states. The Mueller matrix relates the scattering waves to the incident waves and characterizes the random medium at the incident frequency. Once the Mueller matrix is known, the scattering waves at different angles can be determined for any polarized incident wave.

Recent interest has been focused on measuring the Mueller matrices for random media such as nonspherical particles [1], ocean water [2], optical mirrors [3], and biological particles [4]. On the other hand, little has been done on the theoretical calculations of Mueller matrices except for some limited cases. Bickel calculated the Mueller matrices for a single sphere by the Rayleigh and Rayleigh-Gans approximations and the Mie solution [5]; Kattawar calculated the Mueller matrix for dielectric cubes by solving an integral equation [6]; Hofer employed the extended boundary condition, also called the T-matrix method, to compute the Mueller matrices for spheroids [7]. However, the multiple scattering effect is not included in the above calculations.

Multiple scattering effects have been investigated for a number of random medium problems with a slab geometry. A random medium of this kind with linearly polarized incident waves has been studied with the use of vector radiative transfer equation [8]–[10]. Leader [11] and Shin [12] investigated the case of small scatterers for arbitrarily polarized incident waves. However, due to the difficulty in solving the vector radiative transfer equation, the solution has not been obtained for arbitrarily polarized incident waves with arbitrary particle size.

In this paper, the vector radiative transfer equation is solved for scattering intensities from arbitrarily polarized incident waves. The random medium has a plane-parallel slab geometry with randomly distributed spherical particles and with arbitrary size distribution. The refractive index of the slab is allowed to be different from the surrounding media. The multiple scattering effect is included in the calculations. The calculated scattering intensities for four independent polarized incident waves are used to construct the Mueller matrices for the random medium. In addition, the elements of the constructed Mueller matrices shown in this paper meet the conditions discussed in [13] and [14].

Section II describes the matrix representations of the Stokes vectors and Mueller matrix. Sections III and IV formulate and decompose the vector radiative transfer equation which allows us to calculate the scattering wave intensities due to the multiple scattering of the polarized incident wave by the randomly distributed particles. Section V presents the calculations of the Mueller matrices and polarization signatures. Finally the conclusion is given in Section VI.

II. Stokes Vectors and Mueller Matrix

The scattering of a polarized electromagnetic wave by an arbitrary particle may by described by means of a 2×2 amplitude scattering matrix satisfying

$$\begin{pmatrix} E_1^s \\ E_2^s \end{pmatrix} = \frac{e^{ikr}}{r} \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \begin{pmatrix} E_1^{in} \\ E_2^{in} \end{pmatrix}. \tag{1}$$

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Controlled millimeter-wave experiments and numerical simulations on the enhanced backscattering from one-dimensional very rough surfaces

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We present experimental results on the scattering of electromagnetic waves at millimeter-wave frequencies from one-dimensional very rough conducting surfaces with controlled surface roughness statistics. Very rough surfaces are defined as surfaces with rms height and correlation length of the order of a wavelength such that the rms slope is at least unity. It is expected that scattering experiments using these surfaces can provide useful insights since their statistics lie outside the range of validity of the present theories, namely, the Kirchhoff and perturbation theories. Strong backscattering enhancement at different incident angles, both in the transverse electric and transverse magnetic polarizations, are observed experimentally. Numerical calculations based on the exact integral equation method for cylindrical beam wave illumination compare favorably with the experimental results. The agreement between measurements and numerical calculations is good over a wide range of incident angles and for all scattering angles. The close agreement between the experimental results and numerical simulations indicates that this controlled experimental setup can be used to study scattering phenomena from one-dimensional very rough surfaces with different roughness statistics as well as from two-dimensional rough surfaces.

INTRODUCTION

Recently, there has been interest in the phenomenon of backscattering enhancement, also known as the opposition effect, in the scattering of electromagnetic waves from very rough surfaces. The existence of the enhancement has been verified numerically by several authors [*Celli et al.*, 1985; *McGurn and Maradudin*, 1987; *Soto-Crespo and Nieto-Vesperinas*, 1989; *Chen and Ishimaru*, 1990]. Analytical solutions based on the first- and second-order Kirchhoff approximations have been successful in predicting the existence of backscattering enhancement for very rough perfectly conducting, dielectric and metallic surfaces [*Chen and Ishimaru*, 1990]. Experimental verifications of the backscattering enhancement of scattered light from metallic rough surfaces have also been reported independently by several authors [*O'Donnell and Mendez*, 1987; *Haner and Menzies*, 1989; *Gu et al.*, 1989; *Kim et al.*, 1990]. Most of the recently reported experiments are for surfaces in which either the statistics of the surfaces are known approximately by direct measurements, or the statistics of the surfaces can be controlled to some extent. Among the experimental results, O'Donnell et al. were the first to report backscattering enhancement of scattered light from two-dimensional Gaussian random rough surfaces in which the rms roughness and the correlation length of the surface can be controlled [*O'Donnell and Mendez*, 1987]. The desired statistics of the surface can be obtained with some success by controlling the exposure time of a photoresistant surface exposed to a laser speckle pattern which obeys negative exponential intensity statistics [*Gray*, 1978]. Following their work, Kim et al. have extended the results to one-dimensional rough Gaussian surfaces and obtained reasonably good agreement between the experimental and numerical results [*Kim et al.*, 1990]. However, when the surface roughness is of the order of one wavelength, the agreement is good only for small angles of incidence and limited range of observation angles.

As indicated in Figure 1, most of the conventional theories available are applicable in limited regions of validity [*Ishimaru*, 1990] and break down when the roughness of the surface becomes comparable to the wavelength of the incident wave. Few analytical solutions exist for such a problem, and those are only suitable for one-dimensional surfaces in which the height is a random function of posi-

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Wave Propagation in Random Media (Scintillation)

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Preface

In the past several years, there has been a surging interest in wave propagation in random media and an increasing awareness that waves in random media encompass many diverse fields such as atmospheric optics, ocean acoustics, radio physics, astronomy, plasma physics, and condensed-matter physics. In recognition of this interest and recent developments, the first International Meeting on Wave Propagation in Random Media was held in Seattle in August 1992, cochaired by Valerian I. Tatarskii and Akira Ishimaru, with Rod Frehlich as Executive Secretary. The purpose of the meeting was to foster communication and exchange of ideas relating to problems of wave propagation in continuous random media and to promote a multidisciplinary approach to research in scintillation by bringing together the optics, radio, and acoustics communities in this endeavor. The conference attracted two hundred scientists from thirteen countries, including thirty from the former Soviet Union.

All the invited review papers were presented orally, and most of these papers are included in this book. In addition, 130 papers presenting new results were exhibited as posters, and these will be published in *Waves in Random Media,* Institute of Physics Publishing, United Kingdom.

The invited review papers were organized into sessions on scintillation phenomena, statistical description of scintillation, imaging through turbulence, theory, and remote sensing using scintillation. The coverage of the topics is diverse, including optical scintillation in the atmosphere; acoustic fluctuations in the ocean; and radio waves through the ionosphere, interstellar plasmas, planetary atmosphere, and solar wind. Theoretical methods include extended Huygens-Fresnel principle, asymptotic analysis for solutions of moment equations, path-integral techniques, two-scale expansion, multiscreen analysis, and extensive numerical simulations. Also discussed are imaging through turbulence, speckle interferometry, adaptive optics, optical remote sensing, and random gravitational lenses. Throughout the sessions and the panel discussions, it became clear that great progress has been made in wave propagation in random media in many diverse fields. However, it also became evident that further investigations are needed in several areas. Numerical simulations have been recognized as an important benchmark. Intermittency, power law and other spectra, pulse propagation, beam waves, double passage and enhanced backscattering, higher moments, correlations in space and time, spatial and temporal frequencies, and anisotropic random media are among those topics that require further intensive study. Also noted is the need to relate theories to the real atmosphere and ocean for useful applications.

All in all, it was a successful international meeting where scientists and engineers from different disciplines came together to discuss the common theme of wave propagation in random media. This is also an indication that the field of waves in random media has become an important scientific discipline, and it is hoped that the scientific interactions exhibited in this conference will continue to contribute to the advancement of the field. It is also hoped that future conferences will include topics on waves in discrete scatterers and rough surfaces.

In this book, we depart from the original arrangement of the papers for the meeting and present the material in an order more convenient for reading and understanding.

The first section provides an introduction to scintillation phenomena, including theoretical ideas, historical reviews, and classical experimental results for various types of natural media such as the atmosphere, ionosphere, interplanetary plasma, and oceans. Section 2 gives a more detailed review of scintillation measurements of various media and their interpretations based on recent results. Section 3 contains papers whose main goal is to obtain information about the spatial structure of sources or medium characteristics from the scintillating signals. The first three papers are devoted to the problem of image restoration using three principally different approaches, and the other three deal with the remote sensing of the turbulent parameters of such different media as a terrestrial atmosphere or interplanetary plasma.

The next two sections address the theory of wave propagation in random media. Section 4 starts with a review of classical theoretical results concerning the solution of the fourth moment equation, using the perturbation theory and asymptotic methods. The following papers give an idea of how this theory and other similar techniques can be applied to more specific problems such as pulse and beam wave propagation, double passage of a beam through an extended medium, and even propagation in space, taking into account the gravitational effects. Section 5 demonstrates the attempts to improve conventional theory. The authors of this section emphasize the development of more powerful analytical and computational methods that will allow expansion of the applicability of theoretical methods for the description of the diverse and still puzzling scintillation phenomena.

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Rapid Communications

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Velocity of coherent and incoherent electromagnetic waves in a dense strongly scattering medium

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Frequency and time-domain experiments are conducted to present additional confirmation of the slow speed of electromagnetic waves in a dense strongly scattering medium. A wide-band microwave signal is propagated through randomly distributed glass spheres, and the speed is defined as the time at which 50% of the pulse energy arrives. Thus, the speed was measured directly without the use of the transport mean free path and the diffusion coefficient. The speed of an incoherent pulse in the Mie resonance scattering region is found to be less than 40% of the vacuum speed for a fractional volume of 11% consistent with the energy velocity. Since the incoherent wave in a dense medium is the diffuse wave, the velocity presented in this paper corresponds to the velocity of the diffuse wave and it is different from the ballistic velocity. The speed of coherent waves is found to be almost constant and is quite different from the energy velocity.

INTRODUCTION

In recent years, there has been a surge of interest in multiple scattering of waves in random media, particularly in connection with enhanced backscattering and localization.[1–8] Recently, it was shown experimentally and theoretically that the speed of light in strongly scattering media can be reduced to a fraction of the vacuum speed of light.[9] Experimentally, the transport mean free path l is obtained from steady-state measurements and the diffusion coefficient D is obtained from dynamic measurements. According to $D=vl/3$, the velocity v is found to be very low, particularly in the region of resonance scattering of particles where the stored energy is large. It was explained that the velocity v is neither phase nor group velocity, but the energy velocity v_E, and this was confirmed by theoretical study of v_E.[9]

This paper presents additional confirmation of this low speed by performing a pulse propagation experiment at microwave frequencies. Using a network analyzer, frequency and time-domain experiments are conducted for a broadband microwave signal propagating through randomly distributed glass spheres whose sizes are close to a wavelength such that resonance scattering takes place. The transmitted pulse is then decomposed into coherent and incoherent pulses. It is found that the speed, at which 50% of the transmitted incoherent power arrives, is consistent with energy velocity v_E given previously.[9] Since the incoherent wave in a dense medium is the diffuse wave, the velocity presented in this paper corresponds to the velocity of the diffuse wave and it is different from the ballistic velocity. However, it is found that the speed of the coherent pulse is nearly constant and is different from the phase, group, or energy velocity.

The velocity of the electromagnetic waves in random media has been studied extensively in the past. Optical experiments using the picosecond laser and polystyrene micro spheres suspended in water were conducted by several research groups.[10,11] Although these experiments were conducted with several different particle sizes, little experimental data are available for the wide continuous range of size parameters. In particular, the diffuse wave velocity in the Mie resonance scattering region has not been studied extensively. In addition, it is difficult to separate coherent waves from incoherent waves in optical experiments. In this paper, we show microwave pulse propagation experiments using a wide-band microwave system (10–20 and 25–40 GHz band) and glass spheres embedded in styrofoam sheets. This is a dense scattering medium with the fractional volume of 11%. The frequency and particle size were chosen so that the experiment covers the Rayleigh-Mie transition region and Mie resonance scattering region.

EXPERIMENTAL SYSTEM

The experimental system consists of Hewlett Packard network-analyzer- (NWA) based radars operating from 10 to 20 GHz and from 25 to 40 GHz. The time-domain response is obtained by taking the Fourier transform of the frequency domain data with the bandwidth of 2.5 GHz centered at f_0. By shifting the center frequency f_0 from the lower limit to the upper limit and keeping the bandwidth of 2.5 GHz, the pulse arrival time as a func-

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A Banded Matrix Iterative Approach to Monte Carlo Simulations Of Large-Scale Random Rough Surface Scattering: TE Case

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Abstract–A banded matrix iterative approach is applied to study scattering of a TE incident wave from a perfectly conducting one-dimensional random rough surface. It is much faster than the full matrix inversion approach or the conjugate gradient method. When compared to the Kirchhoff iterative approach, it is of comparable CPU time, and works for cases when the Kirchhoff iteration is erroneous. The method is illustrated for a variety of parameters with particular application to large scale rough surface problems. The largest surface length used is 400 wavelengths with 3200 unknowns, and all the coherent wave interactions are included within the entire surface length. The accuracy of the banded iterative approach is demonstrated by showing that the results overlie those of the exact matrix inversion and the conjugate gradient method. The numerical method is also easy to implement. With this approach, we are able to compute the new response characteristics of composite rough surfaces with much larger scales. The case of large incidence angle is also studied. Comparison is also made with the analytic second-order Kirchhoff theory.

I. INTRODUCTION

The study of wave scattering by random rough surfaces is a topic of continuing interest [1–3]. The classical analytic approaches of Kirchhoff approximation and small perturbation method [1–3] have been used to solve problems. However, both are restricted in domain validity. With the advent of modern computers, the Monte Carlo simulations of one-dimensional rough surfaces can be implemented. The standard method is the method of moments [4]. An integral equation method in the space domain is formed and then converted to a matrix equation with a full matrix inversion [5-11]. However, the full matrix inversion requires $O(N^3)$ number of operations where N is the number of unknowns. The typical number of unknowns used is between 300–400 with 5 to 10 unknowns per wavelength. However, for large-scale rough surface problems, a much larger surface length is required. Large-scale problems include cases of large rms heights, large correlation lengths, large incidence angles, composite rough surfaces with small-scale roughness superimposed on large-scale roughness, etc. Thus recently, increasing effort has been invested in finding a more computationally efficient method than the integral equation method of full matrix inversion. One approach is the Kirchhoff iterative approach [11]. The integral equation is cast into the Fredholm equa-

Mueller Matrix Calculation for a Slab of Random Medium with Both Random Rough Surfaces and Discrete Particles

Chi M. Lam, *Member, IEEE*, and Akira Ishimaru, *Fellow, IEEE*

***Abstract*—A model for a slab of random medium containing both random rough surfaces and discrete scatterers is presented in this paper. The refractive indices of the surrounding media are different from the background refractive index of the random medium. Kirchhoff rough surface theory is used to derive the transmittivity and reflectivity matrices for the scattering of electromagnetic waves from the rough surfaces. These matrices are used to determine a pair of boundary conditions for the vector radiative transfer equation. The multiple scattering due to the discrete scatterers is computed by solving the radiative transfer equation numerically, including the rough surface scattering effect. Mueller matrices characterizing the random medium are constructed from the scattered Stokes vectors due to four independent polarized incident waves. The Mueller matrices are found to have symmetrical properties, and there are eight nonvanishing matrix elements.**

I. Introduction

Many objects and matter which exist in nature have irregular shapes and forms. For example, the ocean surface, desert, and terrain have random rough surfaces. However, atmospheric clouds, rain, and biological particles in tissue consist of randomly distributed particles. The propagation of electromagnetic waves are, in general, influenced by the shapes and forms of these scattering objects. An understanding of how electromagnetic waves are affected by media containing such objects may lead to methods of improving radar communications and of providing grounds for interpreting remote sensing measurements.

The problems of scattering of electromagnetic waves by random rough surfaces and randomly distributed particles have been investigated for a number of years. Classical rough surface scattering theories, such as the Kirchhoff and small perturbation, have been applied successfully to rough surfaces with appropriate surface roughness [1]–[4]. On the other hand, radiative transfer theory has been used to evaluate the volume scattering due to the randomly distributed particles [5]–[8]. In this paper, a model which contains both random rough surfaces and randomly distributed particles is presented.

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Previous models which combine the surface and volume scattering effects have been investigated by using the Kirchhoff theory and the vector radiative transfer theory [4]–[11]. Kirchhoff theory associated with the geometric optics approach was used and applied to Gaussian statistical rough surfaces with moderate roughness. The calculated scattering waves contain both coherent and incoherent waves, but they cannot be separated. The Kirchhoff theory is employed again in this paper, but a method other than geometric optics is used to calculate the waves scattering from the Gaussian statistical rough surface (see Section II). The method presented in this paper applies to rough surfaces with surface roughness much less than a wavelength. The calculated scattering waves, however, can be separated into coherent and incoherent parts. The rough surfaces considered in this paper also can be reduced to a planar surface as a special case.

The scattering of electromagnetic waves from rough surfaces with small surface roughness is expressed in terms of the transmittivity and reflectivity matrices. These matrices are then employed to work out a pair of boundary conditions for the vector radiative equation. The volume scattering solution, which is obtained by solving the vector radiative transfer equation with derived boundary conditions, therefore includes the effect of rough surface boundaries.

In this paper, the vector radiative transfer equation with a pair of boundary conditions accounting for the rough surface effect, is solved for incoherent specific intensities from arbitrarily polarized incident waves. The random medium has a slab geometry with both random rough surfaces and randomly distributed spherical particles with Gaussian size distribution. The calculated incoherent specific intensities for four independent polarized incident waves are expressed in terms of Stokes vectors and are used to construct the Mueller matrices, which characterize the random medium.

II. Transmittivity and Reflectivity Matrices

Consider a Gaussian statistical random rough surface, as shown in Fig. 1. The incident wave is a plane wave with polarization state $\hat{e}_i$ and it is propagating in direction $\hat{k}_i$. The Kirchhoff theory, which makes use of the tangential plane, approximation is employed to evaluate the scattered waves. In the tangential plane approximation, the fields at any point on the surface are approximated by the fields that would be present on the tangential plane at that point. The scattered electric fields in the reflection and transmission sides can be

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Pulse broadening and two-frequency mutual coherence function of the scattered wave from rough surfaces

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Abstract. Analytical expressions for the two-frequency mutual coherence function and angular correlation function of the scattered wave from rough surfaces based on the Kirchhoff approximation are presented. The coherence bandwidth depends on the illumination area as well as on the incident and scattered angles and the surface characteristics. Scattered pulse shapes are calculated as the Fourier transform of the two-frequency mutual coherence function. Calculations based on analytical solutions are compared with millimetre wave experimental data and Monte Carlo simulations showing good agreement.

1. Introduction

There has been an increasing interest in and need for understanding pulse broadening and coherence bandwidth in acoustic or electromagnetic waves scattered from rough surfaces [1–6], e.g. in the ocean acoustic scatter channel and SAR remote sensing of earth surfaces. There has also been a strong interest in optical remote sensing of rough surface characteristics utilizing the angular and frequency correlations of the scattered wave [7].

This paper presents a theory for the mutual coherence function based on the Kirchhoff approximation. The results show the effects of the illumination area. Millimetre wave scattering experiments and Monte Carlo simulations are performed on one-dimensional rough surfaces showing good agreement with the analytical results. The theory is applicable to the range of parameters with the RMS slopes less than 0.5 and the correlation distance $l \gtrsim \lambda$. For the case where the RMS slopes are close to one, where backscattering enhancement takes place, the second-order Kirchhoff approximation needs to be included [8, 9]. This will be discussed in a separate paper.

2. Two-frequency mutual coherence function for one-dimensional rough surfaces

The Kirchhoff approximation for the scattered wave from rough surfaces has been extensively studied [1], and therefore we give only a brief summary necessary for our discussion. The far scattered field is given by (figure 1)

$$\Psi_s = k\cos\theta\sqrt{\frac{2\pi}{kR}}\,e^{ikR-i\pi/4}T(\boldsymbol{K},\boldsymbol{K}_i). \tag{1}$$

The transition matrix T is given by

$$T(\boldsymbol{K},\boldsymbol{K}_i) = \frac{F_1}{2\pi}\int R_1 e^{-i(\boldsymbol{K}-\boldsymbol{K}_i)\cdot\boldsymbol{r}_1}\,dx_1 \tag{2}$$

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Optical Multiple Scattering by Particles

Akira Ishimaru *

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Abstract

When an optical beam is incident on particles that are randomly distributed, and if the fractional volume is small, single scattering theory is adequate to explain the scattering characteristics of the medium. However, when the fractional volume is increased, multiple scattering effects cannot be ignored. This paper reviews the fundamental theories of multiple scattering including radiative transfer and diffusion theories. Also included are recent studies on polarization effects, localization, enhanced backscattering, resonant localization, pulse scattering and scattering in dense media.

1 Introduction

The scattering of light by randomly distributed particles has been studied extensively in the past, including its applications in atmospheric optics, optics in the ocean, optical scattering in tissues and blood, optical scattering by vegetation and scintillation by interplanetary and interstellar media [1–10]. In most cases where the distribution of particles is sparse and the fractional volume is small, the single scattering theory is applicable. However, there are many cases where the fractional volume is not small, and multiple scattering and diffusion theories need to be applied in order to explain and predict the scattering phenomena.

In a random distribution of descrete scatterers, waves are scattered and absorbed owing to the inhomogeneities and absorption characteristics of the medium. A mathematical description of the propagation and scattering characteristics of waves can be made in two different manners: analytical theory and transport theory. In analytical theory [1], we start with Maxwell's equations, take into account the statistical nature of the medium and consider the statistical moments of the wave. In principle, this is the most fundamental approach, including all diffraction effects, and many investigations have been made using this approach. However, its drawback is the mathematical complexities involved and its limited usefulness.

Transport theory [1–3, 6, 9–11], on the other hand, does not start with Maxwell's equations. It deals directly with the transport of power through turbid media. The development of the theory is heuristic and lacks the rigor of the analytical theory. Since both the analytical and transport theories deal with the same physical problem, there should be some relationship between them. In fact, many attempts have been made to derive the transport theory from Maxwell's equations with varying degrees of success [2]. In spite of its heuristic development, however, the transport theory has been used extensively, and experimental evidence shows that the transport theory is applicable to a large number of practical problems.

In this paper, we review several theories including the first-order, multiple scattering, transport and diffusion theories. We also discuss some of the more recent theoretical and experimental developments including localization, pulse scattering and dense media. The strong interest in this subject is reflected in the launch of a new journal, *Waves in Random Media,* by the Institute of Physics (UK) in 1991, international workshops on wave propagation in random media held in Tallin, USSR in 1988, on surface and volume scattering held in Madrid in 1988 and on modern analysis of scattering phenomena held in Aix en Provence, France, in 1990 and an international meeting on wave propagation in random media held in Seattle in 1992.

2 Coherent and Incoherent Fields

Consider an optical beam propagating through randomly distributed particles. The locations of the particles vary randomly in space and time, and therefore the amplitude and the phase of the wave also vary randomly in space and time. Suppose that a time-harmonic field with $\exp(-i\omega t)$ is incident on the medium. If we take a component E_x of the field vector $\bar{E}$, the scalar field $u(\bar{r}, t) = E_x$ is a random function of position $\bar{r}$ and time t. We write u as follows:

$$u(\bar{r}, t) = Re[U(\bar{r}, t)\exp(-i\omega t)]\,, \tag{1}$$

where $U(\bar{r}, t) = A(\bar{r}, t)\exp[i\phi(\bar{r}, t)]$ is called the complex envelope and A and ϕ are the random functions. We now write U as the sum of the coherent field $\langle U\rangle$ and the fluctuating field U_f:

$$U(\bar{r}, t) = \langle U(\bar{r}, t)\rangle + U_f(\bar{r}, t)\,, \tag{2}$$

where $\langle\ \rangle$ denotes the ensemble average. In theoretical work, we normally consider the ensemble average, but in practice this can often be approximated by its spatial or time average. The effective propagation constant K for the coherent field $\langle U\rangle$ is defined by

$$(\nabla^2 + K^2)\langle U\rangle = 0\,. \tag{3}$$

An approximate expression for K is given by [1]

$$K = [k^2 + 4\pi\rho f(\hat{i}, \hat{i})]^{1/2} \tag{4}$$

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Copolarized and cross-polarized enhanced backscattering from two-dimensional very rough surfaces at millimeter wave frequencies

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Abstract. Wideband millimeter wave experiments from 75-100 GHz on the scattering from two-dimensional very rough conducting surfaces are presented. The two-dimensional very rough surfaces are manufactured using a computer-numerical-controlled milling machine so that the surface statistics are precisely controlled. The surfaces have both Gaussian roughness statistics and Gaussian surface correlation functions. Bistatic scattering experiments on surfaces with either isotropic or anisotropic correlation functions are performed. Copolarized and cross-polarized bistatic scattering cross sections are measured for both transverse electric and transverse magnetic incidence at 20°. For isotropic surfaces, backscattering enhancement exists for both copolarized and cross-polarized returns and is found to be a function of the surface rms slope. In addition, a strong frequency dependence is observed across the 25-GHz bandwidth in the cross-polarized returns. To investigate the effect of surface correlation anisotropy, scattering experiments on anisotropic rough surfaces are also performed. It is found that the bistatic scattering cross section for an anisotropic surface is a function of the effective correlation length projected along the plane of scattering. Results on the bistatic scattering experiments presented here serve as a motivation to further pursue more elaborate and complete scattering experiments in order to advance research on scattering from very rough surfaces.

Introduction

The scattering of electromagnetic waves from very rough surfaces has been studied analytically, numerically, and experimentally by many authors [*Bennett and Mattsson*, 1989; *Gu et al.*, 1989; *Haner et al.*, 1989; *Ishimaru*, 1990; *Ishimaru and Chen*, 1990; *Ishimaru et al.*, 1991; *Kim et al.*, 1990; *Ogilvy*, 1991; *Phu et al.*, 1993]. Very rough surfaces are those with steep slope and rms roughness characteristics comparable to the wavelength of the incident radiation. The problem has been attracting considerable interest in recent years because of the existence of backscattering enhancement for very rough surfaces. The conventional theories based on the Kirchhoff approximation and the perturbation method are not valid for very rough surfaces and, hence, cannot predict the enhancement [*Ishimaru*, 1990].

For scattering from one-dimensional (1-D) very rough surfaces, different numerical methods were developed to solve for the far-field scattering cross section [*Lou*, 1991; *Lou et al.*, 1991; *Maradudin et al.*, 1990]. However, due to the tremendous requirement for computer memory, the numerical solutions for two-dimensional (2-D) surfaces are very few and are limited to rough surfaces with small roughness [*Fung et al.*, 1990; *Lou*, 1991]. More recent analytical solutions for high slope 1-D very rough surfaces have been successful in predicting the enhanced backscattered peak. The method is based on the second-order

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Pulse broadening of enhanced backscattering from rough surfaces

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Abstract. Recently, we presented a study of pulse scattering by rough surfaces based on the first-order Kirchhoff approximation which is applicable to rough surfaces with RMS slope less than 0.5 and correlation distance $l \gtrsim \lambda$. However, there has been an increased interest in enhanced backscattering from rough surfaces, study of which requires inclusion of the second-order Kirchhoff approximation with shadowing corrections. This paper presents a theory for the two-frequency mutual coherence function in this region and shows that the multiple scattering on the surface gives rise to an additional pulse tail in the direction of enhanced backscattering. The theory predicts pulse broadening approximately 20% greater than that caused by single scattering alone for a delta-function incident pulse and typical surface parameters. Analytical results are compared with Monte Carlo simulations and millimetre-wave experiments for the one-dimensional rough surface with RMS height 1λ and correlation distance 1λ, showing good agreement.

1. Introduction

There has been an increased interest in and need to understand pulse broadening and coherence bandwidth of acoustic and electromagnetic waves scattered from rough surfaces [1–4]. We have recently presented a study of pulse scattering by rough surfaces in the region of surface parameters where the first-order Kirchhoff approximation is applicable [5]. This paper presents an extension of that study to include the region where backscattering takes place. This is the case where the RMS slopes are close to one and the second-order Kirchhoff approximation with shadowing corrections has to be included.

We present analytical expressions for the two-frequency mutual coherence function and angular correlation function of the scattered wave from one-dimensional rough surfaces based on the first- and second-order Kirchhoff approximations with shadowing [6–10]. Scattered pulse shapes are calculated as the Fourier transform of the two-frequency mutual coherence function. We present results from millimetre-wave scattering experiments and Monte Carlo simulations on one-dimensional rough surfaces, which show good agreement with the analytical results. The theory is applicable to the range of parameters with the RMS slopes close to one and the correlation distance $l \gtrsim \lambda$. It is interesting to note that in the region of enhanced backscattering, multiple scattering takes place due to the double bounce of the wave on the surface, and this extra propagation distance on the surface yields a long pulse tail in the enhanced backscattering direction.

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PULSE SCATTERING BY ROUGH SURFACES

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ABSTRACT

This paper first presents a general formulation of the scattered pulse from rough surfaces in terms of the two-frequency mutual coherence function. We define the two-frequency surface cross section per unit area. We then present an example of the two-frequency mutual coherence function using the Kirchhoff approximation for the surface with moderate rms slope.

The results show the effects of the illumination area. The coherence bandwidth increases as the illumination area decreases, resulting in shorter pulse broadening. We report results from Monte Carlo simulations and millimeter wave experiments at 75-100 GHz, involving rough surfaces with given statistics. The simulations and experiments show good agreement with the theory.

We also consider rough surfaces with higher rms slopes. This is the region where enhanced backscattering takes place, caused by the multiple scattering of waves on the rough surface. This multiple scattering results in the narrowing of the two-frequency mutual coherence function and the broadening of the scattered pulse in the backscattered direction. The effects of the illumination area, non-Gaussian spectrum, and rms slopes are investigated and comparisons are made with Monte Carlo simulations and millimeter wave experiments, showing good agreement.

INTRODUCTION

There has been an increasing interest and need for understanding the characteristics of pulses scattered from rough surfaces.[1-6] Examples are the ocean acoustic scatter, SAR remote sensing of the earth surfaces, and the effects of surface clutter on imaging and target detection. There has also been a strong interest in optical remote sensing of rough surface characteristics utilizing the angular and frequency correlations of the scattered wave.

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Experimental Studies of Bistatic Scattering from Two-Dimensional Conducting Random Rough Surfaces

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***Abstract*— Despite the recent development of analytical and numerical techniques for problems of scattering from two-dimensional rough surfaces, very few experimental studies were available for verification. In this paper, we present the results of millimeter-wave experiments on scattering from two-dimensional conducting random rough surfaces with Gaussian surface roughness statistics. Machine-fabricated rough surfaces with controlled roughness statistics were examined. Special attention was paid to surfaces with large rms slopes (ranging from 0.35 to 1.00) for which enhanced backscattering is expected to take place. Experimentally, such enhancement was indeed observed in both the copolarized and cross-polarized returns. In addition, it was noticed that at moderate angles of incidence, the scattering profile as a function of observation angle is fairly independent of the incident polarization and operating frequency. This independence justifies the use of the geometric optics approximation embodied in the Kirchhoff formulation for surfaces with large surface radius of curvature. When compared with the experimental data, this analytical technique demonstrates good agreement with the experimental data.**

I. Introduction

Electromagnetic wave scattering from random rough surfaces emerged as a distinct discipline of considerable research interest in many areas including remote sensing, surface optics, ocean acoustics, and ultrasound imaging of biological tissues [1]–[5]. Earlier work on surface scattering mainly focused on scattering from one-dimensional conducting random rough surfaces at optical and millimeter-wave frequencies, and fruitful results were reported in various numerical, analytical, and experimental studies [6]–[9], [16]–[18]. However, the roughness of most naturally occurring surfaces is two-dimensional instead of one-dimensional in nature. In order to address practical application-oriented situations, research on two-dimensional surface scattering has become important. Because of the inherent complexity involved, it is not until only recently that several numerical and analytical techniques [10]–[13] have become available for two-dimensional surface scattering problems. Similar work on experimental studies, however, has been very limited in quantity for verification [6], [14]. For this reason, in this paper we present detailed experimental studies on scattering from two-dimensional conducting random rough surfaces. Isotropic two-dimensional rough surfaces with known Gaussian height distribution and Gaussian surface correlation function were machine-fabricated by means of a CAD/CAM process, and scattering experiments were conducted using a wideband polarimetric scattereometer operating at millimeter-wave frequencies from 75 to 100 GHz. Bistatic cross section (BCS) as a function of incident angle, incident polarization, frequency, and surface roughness was measured and compared with the analytical calculations based on the second-order Kirchhoff approximation with angular and propagation shadowing corrections [13].

The entire experimental study consisted of three parts: 1) surface profile generation; 2) surface fabrication; and 3) bistatic cross-sectional measurement.

II. Surface Profile Generation

Two-dimensional conducting random rough surfaces with Gaussian roughness statistics were examined in this paper. Mathematically, these surfaces can be described by the probability density function $P(z)$ of the surface height z and the surface correlation function $C(\tau_x, \tau_y)$

$$P(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma^2}\right) \tag{1}$$

$$C(\tau_x, \tau_y) = \sigma^2 \exp\left[-\frac{1}{\ell^2}(\tau_x^2 + \tau_y^2)\right] \tag{2}$$

where σ^2 is the mean-square surface height, ℓ is the correlation length in the x and y directions, and τ_x and τ_y represent the distances between any two points on the surfaces along the x and y directions, respectively. Qualitatively, for a given σ large values of ℓ give rise to slightly rough surfaces, whereas small values of ℓ result in very rough surfaces. For surfaces characterized by Gaussian roughness statistics, a given pair of σ and ℓ defines statistically a unique surface profile.

In order to obtain an accurate representation of a surface profile, the coordinates of each point on the profile must be determined. On this issue, the Spectrum Method [15] was employed in which a two-dimensional Fourier transform is first applied to the surface correlation function $C(\tau_x, \tau_y)$

$$C(\tau_x, \tau_y) \overset{\mathcal{F}}{\rightleftharpoons} W(k_x, k_y) = \frac{\sigma^2\ell^2}{4\pi} \exp\left[-\frac{1}{4}\ell^2(k_x^2 + k_y^2)\right] \tag{3}$$

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Angular correlation function based on the second-order Kirchhoff approximation and comparison with experiments

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The angular correlation function (ACF) of scattering amplitudes is presented using the second-order Kirchhoff approximation (KA) with angular and propagation shadowing functions. The theory is applicable to surfaces with large radii of curvature and high slopes of the order of unity. The correlation consists of contributions from single and second-order scattering. The single scattering provides the necessary condition for substantial correlation to occur. The second-order scattering yields high peaks in the correlation function. The ladder term gives a peak when two waves that have the same incident and scattering angles are traveling in the same direction. The cyclic term gives another peak in the time-reversed direction. These two peaks are related by the reciprocity condition. Although the second-order KA contains several approximations and the solution is simplified to yield a numerically tractable form, its agreement with experimental results is excellent. The theory correctly shows the peaks in the ACF observed in both co-polarization and cross-polarization responses. The width of the memory line is also very close to the value predicted by the theory. © 1996 Optical Society of America

1. INTRODUCTION

The propagation and the scattering of waves in random media have been studied extensively in recent years.[1–3] In addition to the traditional applications of the cross section or the power of the scattered fields, correlations of the scattered waves have been proposed and have stimulated even more intensive research activities.[4–9] In general, the scattered electromagnetic wave varies as a function of position, angle, frequency, and polarization. By combining these variables, one can form different correlations including angular, polarization, and frequency correlations. These correlations give rise to various interesting phenomena, such as angular memory effect, polarization correlation, pulse broadening, and long-range correlation.[9–12] Theoretical, numerical, and experimental studies of waves scattering from rough surfaces[13–15] could then be applied to these correlation phenomena.[11,16–18]

Recently, it has been shown that a change in the direction of the incident wave going through a random medium is "remembered" by the scattered wave.[4] This is known as the memory effect and can be obtained by taking an angular correlation of two waves. The memory effect can be stated as follows. Let $E_s(\theta_i, \theta)$ be the scattered wave observed at the scattering angle θ when the incident angle is θ_i. Suppose that the incident angle is changed from θ_i to θ_i' and that the scattered wave $E_s(\theta_i', \theta')$ is observed at θ'. Initially, it appeared that the scattered wave $E_s(\theta_i', \theta')$ at θ' was not sensitive to the change of the incident angle from θ_i to θ_i' under a multiple-scattering situation. Recent studies show, however, that the angular correlation between $E_s(\theta_i, \theta)$ and $E_s(\theta_i', \theta')$ is very sensitive to the change of the incident angle, thus showing that the scattered wave remembers the direction of the incident angle. This correlation function is defined as

$$\Gamma(\theta_i', \theta'; \theta_i, \theta) = \langle E_s(\theta_i, \theta) E_s^*(\theta_i', \theta') \rangle , \qquad (1)$$

where the angle brackets denote the ensemble average. As long as the difference in the transverse wave numbers is the same for the incident and scattered waves, there will be a strong correlation for $\Gamma(\theta_i', \theta'; \theta_i, \theta)$, indicating the memory effect.

In order to enhance the applicable region of the Kirchhoff approximation (KA) beyond the traditional first-order solution, Ishimaru *et al.*[13,19] have developed the second-order KA for waves scattering from random rough surfaces with large radii of curvature and high slopes (0.5–1.5). This theory employs the proper angular and propagation shadowing functions to correct for higher-order scattering beyond that of second order. Although the second-order KA is based on a number of approximations, including the geometrical optics approximation, the approximate forms of the shadowing functions, and the approximations in reducing the fourfold integrals to double integrals, excellent agreement with carefully controlled millimeter-wave (MMW) experiments was achieved.[19] In addition, it is the first theory to offer a correct interpretation of backscattering enhancement from very rough surfaces.[3]

In this paper we will present the derivation of the angular correlation function (ACF) of scattering fields from two-dimensional (2-D) random rough surfaces using the second-order KA. The surfaces are assumed to have Gaussian statistics determined by two parameters, rms height (σ) and correlation length (l). As in the case of calculating the bistatic cross sections, the angular correlation consists of contributions from single scattering and multiple scattering. The second-order scattering is

Sizing Emboli in Blood Using Pulse Doppler Ultrasound—II: Effects of Beam Refraction

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***Abstract*—A theoretical and numerical study of the acoustic field intensity within a curved flow conduit having 1) diameter similar to the wavelength of the interrogating frequency and 2) speed of sound mismatch with the surrounding medium is presented. The field intensity is shown to vary significantly and in a monotonic fashion across the flow conduit. The resulting insonation of emboli transiting through the Doppler sample volume is explored with a Monte Carlo study of the behavior of the embolus to blood power ratio (EBR). The numerical simulation findings are shown to be in good agreement with previously reported experimental results. A method is explored for estimating embolus diameter when this refraction artifact is present, and shown to yield excellent results when applied to experimental data. Further work toward clinical application of these results is discussed.**

I. Introduction

In previous work, the embolus to blood ratio (EBR) model was proposed by Moehring and Klepper [1] as a tool for detecting, sizing, and characterizing microemboli in flowing blood using pulse Doppler ultrasound. The EBR model is based on measuring the ratio of backscattered power from an embolus to the backscattered power from blood flowing in a pulse Doppler sample volume. The EBR model yields information on embolus size and composition based on multi-frequency interrogation of the embolus. This model was tested by Moehring and Ritcey [2] on a phantom flow loop using a specially designed dual-frequency Doppler. In the course of the experimental investigation, significant spread in the measured EBR for polystyrene microspheres nominally of equal diameter was noted. It was hypothesized that this data spread was due to a speed of sound mismatch between two different media comprising the phantom. The sound beam refraction caused by this mismatch resulted in a nonuniformly insonated sample volume and thus a spread in the backscattered power from emboli transiting different regions of the sample volume.

The work presented here is a theoretical and numerical validation of the hypothesis that beam refraction, measured *in vitro* and anticipated *in vivo*, has a significant yet predictable effect on EBR measurements. To this end, beam refraction due to speed of sound mismatch between a gel and a fluid traveling in a conduit through the gel is theoretically modeled and numerically simulated. Emboli having a normal distribution of diameters about a mean diameter are simulated at random positions within the flow conduit, and the EBR resulting from the refraction-perturbed beam is calculated. The goal in this effort is to determine if the distribution of EBR values created in this simulation is similar to the distribution observed experimentally.

This work is not only important in explaining *in vitro* artifact, but as well is relevant regarding anticipated *in vivo* artifact in clinical studies. The human body presents many windows from which emboli can be studied, and they vary widely in the degree of refraction presented to an interrogating ultrasound beam. Perhaps the most severely refracting tissue environment is the transtemporal approach to the middle cerebral circulation, and this is a widely used venue for detecting microemboli. A basic assumption of the EBR model is that the blood in the Doppler sample volume is uniformly insonated. As will be shown, small changes in the speed of sound (about 3.5% in this study) can yield significant and undesirable modulations in beam sensitivity. It is therefore important to anticipate refraction artifact and determine to what degree sizing and characterizing microemboli *in vivo* can be done in its presence.

Section II begins with a theoretical analysis of beam refraction into a curved flow conduit closely matched to the radius of curvature used experimentally. The analytical expression of the acoustic field is followed by development of a Monte Carlo simulation of emboli transiting the Doppler sample volume positioned within the flow conduit. In Section III, the numerical field calculations are reviewed, and Sections IV and V discuss results of the Monte Carlo simulation, and make comparisons with experimental data.

II. Theory

The theoretical foundation for approximating the acoustic field within the experimental flow conduit is now developed. The approach taken is to propagate a grid of acoustic rays to the conduit surface and calculate the complex field (phase and amplitude) at the tubing surface and on the flow medium side of the interface. The surface of the flow conduit is an interface between a gel and flow within the conduit, and there is no third material such as a thin-walled tube that adds structural support. Calculation of the field within the flow medium requires determining the refraction angle at the tubing surface, given the direction vector of the incident ray and an analytical description of the surface. Also, the transmission coefficient across the interface must be calculated. In order to study the field *within* the tube in the region of interest from

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POLARIMETRIC SCATTERING THEORY FOR HIGH SLOPE ROUGH SURFACES

A. Ishimaru, C. Le, Y. Kuga, L. A. Sengers and T. K. Chan

1. Introduction

Electromagnetic scattering by rough surfaces is important in several disciplines including geophysical remote sensing, ocean acoustics, surface optics, and ultrasound imaging of biological media [1]-[24]. For surfaces with small rms height, the conventional perturbation theory is applicable while for surfaces with large radii of curvature, Kirchhoff theory gives good solutions. In recent years, several improved theories have been proposed to extend the range of validity of surface parameters, and numerical simulation studies have been reported [5]-[24]. This paper presents a theory based on the first and second Kirchhoff approx-

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Angular memory effect of millimeter-wave scattering from two-dimensional conducting random rough surfaces

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Abstract. An experimental study was conducted to investigate the angular memory effect of millimeter-wave scattering from two-dimensional conducting random rough surfaces. The surfaces under investigation were machine-fabricated with known Gaussian roughness statistics, and the copolarized and cross-polarized angular correlation functions (ACFs) of scattering amplitudes were measured. It was found that for the case of reference antenna positions located bistatically in a backward direction, the measured ACF exhibits broad response when single scattering dominates but two peaks when multiple scattering dominates. These observations are in good agreement with the second-order Kirchhoff approximation (KA2). Specifically, the observed broad and peak responses are analytically identified to be due to the first-order and second-order (ladder and cyclical) scattering components, respectively, in KA2.

1. Introduction

When a wave is incident upon a two-dimensional rough surface, it undergoes variable degrees of multiple scattering and depolarization, depending upon surface roughness. The resulting copolarized and cross-polarized scattered waves are in general in all directions and exhibit completely random phase fluctuations. At first glance, it is tempting to assume that these waves contain no information about the direction of the original incident wave.

In a series of theoretical and experimental studies on wave transmission in diffusive media [*Feng et al.,* 1988; *Freund and Rosenbluh,* 1988], however, it was found that the direction of incident waves can be deduced from diffused intensity measurements by virtue of a phenomenon known as the angular memory effect. Basically, this effect describes how the changes in the direction of the incident wave are "remembered" by the diffused scattered waves through a quantitative measure called the angular correlation function (ACF).

Earlier studies on the angular correlations of scattering amplitudes or intensities in response to changes in the direction of the incident wave mainly focused

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INVITED PAPER Special Issue on Electromagnetic Theory—Foundations and Applications

Recent Advances in Multiple Scattering Theories and Applications

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SUMMARY There has been an increasing interest in multiple scattering phenomena in recent years. This is primarily due to the discovery of new multiple scattering phenomena and an increasing awareness that a common thread underlies the work of many researchers in such diverse fields as atmospheric optics, ocean acoustics, radio physics, astrophysics, condensed matter physics, plasma physics, geophysics, bioengineering, etc. In addition, waves in random media is one of the most challenging problems to theoreticians. Thus the field of wave propagation and scattering encompasses the most practical as well as the most theoretical questions. The strong interest in this subject is reflected in the launch of a new journal, Waves in Random Media, by the Institute of Physics, United Kingdom in 1991. This paper reviews some of the most recent developments and discoveries in the field of wave propagation and scattering in turbulence and volume and surface scattering. Included are new discoveries of backscattering enhancement and memory effects which may be applicable to tissue optics, ultrasound imaging, ocean acoustics and geophysical remote sensing. Also indicated are recent developments of numerical Monte-Carlo techniques and experimental studies on this subject.
key words: multiple scattering, random media

1. Introduction

Many natural and man-made media such as the atmosphere, oceans, geophysical media, biological media, and composite and disordered materials have random spatial inhomogeneities and vary randomly in time, and these media are called "random media." Microwaves, optical waves, and acoustic waves propagating in these media experience random fluctuations in space and time, and these fluctuations affect a broad range of practical problems such as communications, remote-sensing, imaging, and object identification. In addition, waves in random media present one of the most challenging problems to theoreticians.

General reviews and detailed expositions are given in several books [1]–[25]. This paper is divided into five sections. In Sect. 2, we discuss wave propagation in turbulence and random continuum where the refractive index is a random function of space and time. Examples are optical propagation in the atmosphere, microwaves in the troposphere, ionosphere, planetary atmosphere, and solarwind, and acoustic scattering in the ocean turbulence. Section 3 is devoted to volume multiple scattering. Examples are optical and microwave scattering by rain, fog, smog, snow, ice particles, and vegetation, optical and ultrasound scattering by tissues and blood, optical and acoustic scattering in the ocean, and scattering in composite materials. In Sect. 4, we discuss scattering by rough surfaces and interfaces. Examples are acoustic scattering by ocean surfaces, microwave and optical scattering by vegetation, terrain, and snow cover, and ultrasound scattering by rough interfaces in biological media. In Sects. 5 and 6, we discuss recent research on coherent backscattering enhancement phenomena and memory effects.

2. Wave Propagation and Scattering in Turbulence and Random Continuum

Extensive work has been already done to obtain the first moment $\langle U\rangle$ and the second moment $\langle U(x,\bar{\rho}_1)U^*(x,\bar{\rho}_1')\rangle$ where x is the propagation distance and $\bar{\rho}$ is the transverse distance [1],[2]. The fourth moment has also been studied extensively.

One of the important developments in this area is the numerical simulation of wave propagation in turbulence [26]. This is a numerical experiment, rather than an actual field experiment. However, it is flexible and can include different spectra, inner scales, etc, although it requires extensive computer capabilities.

The higher-order moment equation has been obtained for the fourth moment [27] using functional integral [28] and path-integral techniques [29], and numerical simulation [26],[30]. The question of how the variation of the background profile affects the intensity fluctuation is also studied [31]. The correlation between the forward and backward waves contributes to the backscattering enhancement [32]–[34]. The scalar wave equation needs to be extended to include the cross polarization effects. For weak fluctuation, the probability density function (PDF) is log normal. However, for strong fluctuation, the I-K distribution is shown to be applicable [35],[36].

An interesting twist in the investigations of radio scattering phenomena by turbulent media is the case of the solar corona. Recent studies based on a synthesis of results from intensity scintillation, phase scintillation, angular broadening, and spectral broadening have shown that, in addition to turbulence that is convected

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